

START-TO-END (S2E) SIMULATION FOR PAL XFEL PROJECT

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Abstract

To generate ultrashort, ultrabright, and coherent X-ray SASE sources, we should supply high quality electron beams to a long undulator. In this paper, we describe design concepts of the new injector, bunch compressors, linac optimization, and start-to-end (S2E) simulation for the Pohang Accelerator Laboratory X-ray Free Electron Laser (PAL XFEL) project.

INTRODUCTION

During the nominal operation of the Pohang Light Source (PLS) storage ring, 2.5 GeV PLS linac is operated as a full energy injector for the ring, and its total injection time is within about 20 minutes a day. Since the PLS linac does not have any other special dedicated service, the linac can be ideally converted into the FEL driving linac for an X-ray FEL facility. To supply femtosecond (fs) hard X-ray SASE sources, recently, Korean government is under considering the PLS linac upgrade for the PAL XFEL project. Under the fundamental mode operation of the PAL XFEL facility, its tunable shortest wavelength is 3 Å, and SASE sources with more shorter wavelength can be also available by various higher harmonic generation technologies [1]. Detail FEL related parameters for the PAL XFEL project can be found in reference [2], and its required electron beam parameters for 3 Å and 1 Å SASE sources are summarized in Table 1. Generally, SASE source properties strongly depend on the electron beam parameters such as slice and projected normalized rms emittances, slice rms relative energy spread, and peak current. And these parameters are mainly determined by the injector system and bunch compressors (BCs) in the FEL driving linac. Since the current 80 kV DC gun can not generate high quality electron beams, a new S-band photoinjector, two bunch compressors, and a new 0.7 GeV injector linac will be added to the existing PLS linac to generate required electron beams for the PAL XFEL project. In this paper, we propose one possible linac layout (05DEC03 version) for the PAL XFEL project and describe its S2E simulation results with ASTRA and ELEGANT codes.

INJECTOR FOR PAL XFEL PROJECT

Recently, by the help of a flat-top laser profile with about 9 ps (FWHM) length and about 1.5 ps rising and falling time, one BNL/SLAC/UCLA type S-band RF gun with a 14 MeV booster linac had generated high quality electron

Table 1: Main parameters for PAL XFEL project.

Parameter	Unit	3 Å / 1 Å
beam energy E	GeV	3.0 / 3.0
single bunch charge Q	nC	1.0 / 1.0
slice normalized rms emittance ϵ_{ns}	μm	1.5 / 1.0
slice rms relative energy spread $\sigma_{\delta s}$	10^{-4}	2.0 / 2.0
peak current I_{pk}	A	4.0 / 4.0
undulator length for fundamental mode	m	60 / 37
undulator length for the 3rd harmonic	m	0.0 / 23

beams with a projected normalized rms emittance of about 1.2 μm for 1 nC single bunch charge [3]. After considering two facts that slice normalized rms emittance should be smaller than 1.0 μm to generate 1 Å SASE source, and projected and slice emittances can be diluted at bunch compressors due to the microbunching instability and CSR, we determined that the PAL XFEL injector should supply much higher quality electron beams with a smaller projected normalized rms emittance [4].

This required higher quality electron beams can be generated by upgrading the BNL/SLAC/UCLA type S-band RF gun with following steps [3]: First, transverse laser profile will be improved to have a good homogeneous intensity, and longitudinal laser profile will be improved to have a good uniform flat-top shape with a shorter rising and falling time. These improvements will help in reducing emittance growth at head and tail regions due to the nonlinear space charge force. Second, the maximum gradient at the cathode will be increased from current 100 MV/m to 120 MV/m which will also help in reducing space charge force effects [5]. Third, we will align laser on the cathode and correct solenoid misalignments by the beam based alignment. Fourth, several fine optimizations will be done under 120 MV/m gradient: gun RF phase optimization to get the maximum energy gain, laser pulse length optimization to control longitudinal space charge force, laser spot-size optimization at the cathode to control transverse space charge force and thermal emittance, solenoid current optimization to compensate emittance growth in gun region due to space charge force and to reduce emittance growth due to the non-zero magnetic field on the cathode [5], [6]. Fifth, we will re-compensate the second emittance growth due to space charge force in the drift space between gun and the booster linac by installing the first S-band accelerating column (X1A) at the so-called *Ferrario matching point* as shown in Figs. 1 and 2 [7]. Here, X1A has a lower

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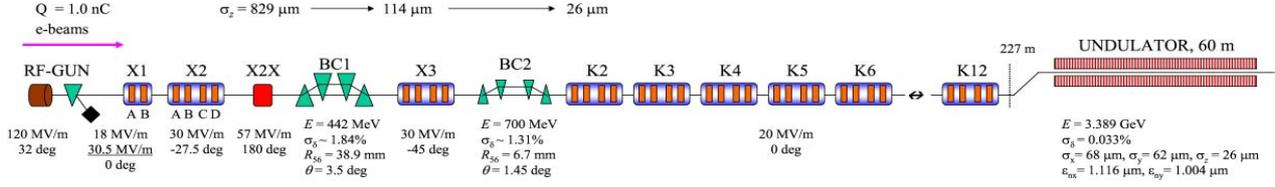


Figure 1: One possible linac layout (05DEC03 version) for PAL XFEL project.

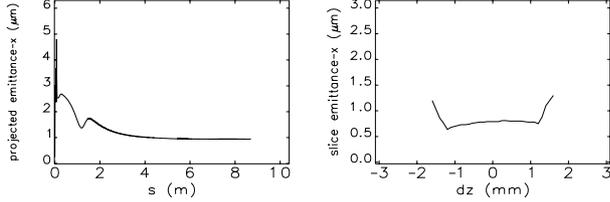


Figure 2: ASTRA simulation results on PAL XFEL injector: (left) projected normalized rms horizontal emittance up to the end of X1B, and (right) slice normalized rms horizontal emittance at the end of X1B. Here the entrance of X1A and X1B are located at 1.4 m and 5.4 m downstream from the cathode, respectively.

gradient to satisfy the *Ferrario matching condition* and the second accelerating column (X1B) has a higher gradient to get a higher beam energy and to control Twiss parameters in X1B [7]. According to our ASTRA simulations for the PAL XFEL injector, we may generate higher quality electron beams with a projected normalized rms emittance of around $0.94 \mu\text{m}$ by following above optimization steps. Its simulation results are shown in Fig. 2, and its detail simulation conditions are summarized in Table 2.

BC FOR PAL XFEL PROJECT

Basic bunch compressor design concepts are well described in reference [8]. The same concepts are used in designing bunch compressors for the PAL XFEL project.

To avoid slice parameter dilution due to the microbunching instability in BCs, we have adopted followings in our linac layout as shown Fig. 1: First, the S-type chicane is generally useful in compensating the projected emittance growth because dispersion is reversed inside of the S-type chicane [9]. If current density profile and/or energy profile have a modulation before the S-type chicane with six dipoles, however, its CSR microbunching instability is much stronger than that of the normal chicane with four dipoles [9]. Therefore, to reduce the microbunching instability and overall CSR strength, we choose only two bunch compressors with the normal chicane instead of the S-type chicane. Second, to keep the slice rms relative energy spread at the entrance of BC2 large, we put BC2 at a low beam energy of around 700 MeV. In this case, BC2 has still a large projected rms relative energy spread of around 1.31%. Third, during compression in BCs, slice energy

Table 2: S2E simulation results for PAL XFEL project.

Parameter	Unit	Value
RF frequency of gun and linac	MHz	2856
repetition rate	Hz	60
gun cell number	cell	1.6
laser spotsize at cathode σ_r	mm	0.60
laser pulse length (FWHM)	ps	10
laser pulse rising and falling time	ps	0.7
normalized thermal emittance	μm	0.60
maximum longitudinal solenoid field	T	0.272
maximum gradient at the cathode	MV/m	120
gun phase from zero crossing	deg	32
low / high accelerating gradient in X1	MV/m	18/ 31
X1 phase from on crest	deg	0.0
projected emittance before BC1 / BC2	μm	0.95 / 1.07
slice emittance before BC1 / BC2	μm	0.83 / 0.84
bunch length before BC1 / BC2	μm	829 / 114
beam energy before BC1 / BC2	MeV	442 / 442
projected energy spread before BC1 / BC2	%	1.84 / 1.31
slice energy spread before BC1 / BC2	10^{-5}	0.92 / 4.3
projected emittance after BC2 / LINAC	μm	1.09 / 1.12
slice emittance after BC2 / LINAC	μm	0.85 / 0.85
bunch length after BC2 / LINAC	μm	26.4 / 26.4
beam energy after BC2 / LINAC	GeV	0.70 / 3.39
projected energy spread after BC2 / LINAC	%	1.27 / 0.03
slice energy spread after BC2 / LINAC	10^{-4}	2.44 / 0.54

spread generally becomes larger to conserve the normalized longitudinal emittance. Therefore slice rms relative energy spread before BC2 can be further increased up to 4.3×10^{-5} by compressing bunch length at BC1 strongly. Since the compression factor at BC1 is high, we put BC1 at 442 MeV to avoid any beam dilution due to space charge force. Note that our linac layout can be also operated as the double chicane mode only by turning off one S-band accelerating section (X3) and by rematching optics [10]. In this case, microbunching instability will be effectively damped by the Landau damping [4], [10].

To avoid projected emittance dilution due to CSR in BCs, we have adopted followings in the PAL XFEL linac layout as shown in Figs. 1 and 3: First, to reduce CSR, we should choose a smaller momentum compaction factor R_{56} of chicane. This is possible by choosing a somewhat larger projected rms relative energy spread σ_δ [8]. Af-

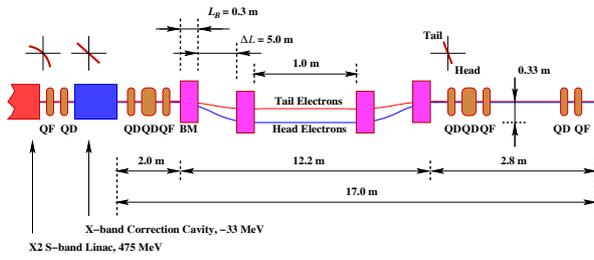


Figure 3: BC1 layout for PAL XFEL project. BC2 chicane has the same layout.

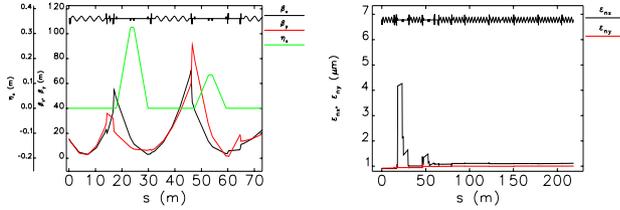


Figure 4: Twiss parameters around BCs (left) and projected normalized rms emittances along PAL XFEL linac (right).

ter considering the emittance growth due to chromatic effect, we choose 1.84% at BC1. Second, we choose short quadrupoles around BCs to reduce emittance growth due to chromatic effect. Third, for a required R_{56} , we can reduce dipole bending angle (hence, CSR) further by using a longer drift space ΔL between the first dipole and the second one as shown in Fig. 3 [8]. Fourth, generally, CSR is weaker at BC1, and CSR becomes stronger at BC2 as bunch length is compressed. Hence, we choose a higher compression factor at BC1 and a lower compression factor at BC2 to reduce overall CSR effects in our two BCs. Fifth, we reduce CSR further by installing a 4th harmonic X-band accelerating column (X2X) before BC1 to compensate nonlinearities in the longitudinal phase space as shown in Fig. 3 [8]. Sixth, if we use a long linac between BCs, the longitudinal short-range wakefield in the linac induces a small change in the longitudinal-phase-space chirping slope at head and tail regions, where charge is low. In this case, projected emittance is increased due to over-compression at head and tail regions in BC2 [7]. Therefore we reduce the length of S-band linac between BCs to reduce the projected emittance growth at BC2. Seventh, the projected emittance dilution due to CSR can be reduced further by forcing the beam waist close to the last dipole where α -functions are zero, and β -functions are their minimum as shown in Fig. 4 [8]. Since chromatic effects becomes smaller at BC2 due to smaller σ_δ , we choose much higher β -functions at the upstream of BC2 to give strong focusing in BC2 as shown in Fig. 4(left) [8]. In this case, the projected emittance growth due to CSR can be effectively reduced at BC2.

To check performance of our linac, we have performed S2E simulation with ASTRA and ELEGANT codes as

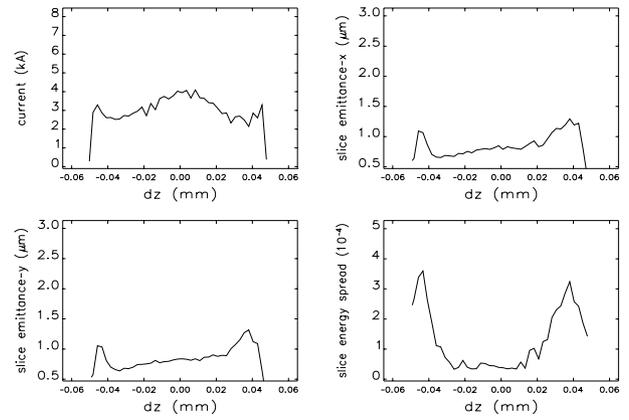


Figure 5: Slice parameters at the end of PAL XFEL linac.

shown in Figs. 1 and 4(right), and as summarized in Table 2 [11]. Here emittance, energy spread, and bunch length are estimated in *normalized rms*, *rms relative*, and *rms*, respectively, and slice parameters before BC2 (after BC2) are estimated at ± 0.1 mm (± 0.02 mm) core region. In these simulations, we have included all important impedances such as space charge force in gun and X1 accelerating section, CSR and incoherent synchrotron radiation (ISR) in BCs, and short-range wakefields in all accelerating sections. According to our S2E simulations, slice parameters in core region are much better than our requirements as summarized in Table 2 and shown in Fig. 5 [11].

SUMMARY

By putting BC2 at a lower energy region, by using a short linac between BCs, and by choosing high compression factor at BC1, slice energy spread before BC2 is about 4.3×10^{-5} , which is large enough to control microbunching instability at BC2. In this case, optimized parameters at the end of PAL XFEL linac are also much better than requirements, and slice and projected normalized rms horizontal emittance growths in BCs are only $0.02 \mu\text{m}$ and $0.14 \mu\text{m}$, respectively, even though peak current is about 4.0 kA.

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